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14. ABSTRACT

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The Impact of a Single Wall on the Stability of the Spray Produced by a Gas-Centered Swirl Coaxial Injector

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Abstract

Studies of injectors often utilize a single, isolated atomizer. In most applications, however, the atomizer is not isolated but is near one or more walls. It has been established that walls affect the expansion and stability of single-phase jets. Under study here is the effect of a single wall on spray behavior, specifically attachment length, spreading and stability. The atomizer being studied is a gas-centered swirl coaxial injector which relies on a dominant gas flow to drive the atomization. High-speed images are analyzed to assess the spray's behavior both qualitatively and quantitatively. Two different wall offset ratios, 0.83 and 1.16, are compared to the free spray. While both walls spacings affect the spray by reducing the spreading, only the 0.83 spacing shows an ability to stabilize the spray.

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Introduction

Offset jets, i.e. jets which issue forth parallel and near but not against a wall, are common in many situations such as air conditioning, burners and internal combustion engines (ICE). As a result, offset jets have been extensively studied, especially from the 1960's to 1980's ([1-3], for example). In recent years they have received considerably less attention, much of it focused on CFD modeling ([4], for example). The majority of the literature, past and present, focuses on single-phase flow, generally gas, in a two-dimensional geometry—a planar jet. Yet, it is not uncommon for offset jets to be found in liquid-gas systems, and a majority of these two-phase systems employ a three-dimensional geometry—an initially round jet offset from a planar wall. Here, the effect of a wall on a two-phase flow arising from an airblast, rocket injector, termed a gas-centered swirl coaxial (GCSC) injector, is studied.

Figure 1 shows the basic structure of a single-phase offset jet along with important geometric parameters. Notice that this configuration and the resulting jet evolution differ from the impinging jet or wall jet configuration. An offset jet is initially pulled towards the wall due to the lower pressure zone created close to the jet exit as a result of the partially-confined flow entrainment. At some downstream region, typically called the attachment or reattachment point, the jet attaches to the wall. Here, part of the inner fluid of the jet is directed upstream into the recirculation zone (due to the pressure gradient). The rest of the jet continues downstream eventually developing to resemble wall-jet flow. As would be expected, the initial shape of the jet, e.g. round or planar, has a dramatic impact on the evolution of this flow, especially in the area from reattachment to wall-jet development [2].

For two-phase flow (liquid droplets suspended in a gas), liquid will be deposited on the wall at and downstream of the reattachment point, and some amount of liquid may be directed upstream of this point due to the pressure gradient. This wetted layer will cause the two-phase jet to develop differently from a single-phase jet. A no-slip velocity boundary condition will no longer apply at the wall; studies of jets offset from free surfaces show that the change in boundary conditions can have dramatic effects on jet development and behavior [5]. However, the two-phase jet will not behave as a jet offset from a free surface because the wall-bound wetted layer cannot behave as the free surface would (for example, it does not possess the deflection capabilities that a free surface does). Some cases of liquid jets and their sprays issuing into gaseous environments near parallel and shallow angle walls have been studied for diesel injectors [6] but they give very little indication of the effects of the wetted wall on the jet behavior. In

difference to diesel sprays, the situation in the current study involves a gas-dominated spray—a high-velocity gas jet with droplets suspended within it. Very little literature exists for this configuration with previous literature applied to coaxial injectors with annular gas flow which would, in effect, shield the wall from the liquid [7].

The flow here is further complicated because the atomized droplets start out as a swirling liquid sheet; while the gas is initially unswirled, tangential velocity may be imparted to it by the liquid. It is well-known that swirling gas flows can develop dynamic behaviors, for example a precessing vortex core (PVC) where a main vortex is formed which is offset from the jet axis and precesses about this axis [8]. Studies have indicated that multiphase flows are more prone to the development of organized dynamic behaviors than single-phase jets and may develop these behaviors at extremely low swirl numbers [9]. Earlier studies of free sprays from gas-centered swirl coaxial injectors have clearly indicated regular, dynamic behavior, although its exact cause is not yet known [10]. Furthermore, it is clear that confinement has an impact on the dynamic behaviors such as PVC and their development [9], but it remains unclear what impact a single, offset wall might have.

The spray and flow in the vicinity of the wall are important for resolving issues of wall compatibility in rocket engines. In a liquid-fueled system the walls may be cooled when the liquid is deposited on and evaporated from the walls. However, if too much liquid is deposited, the engine's performance is adversely affected. Because the liquid's cooling potential is often needed to ensure that the walls maintain an acceptable temperature, it is important to be able to predict where the spray will attach to the wall. Two-dimensional-single-phase jet studies clearly show that the wall alters the shear layer opposite (i.e., away from) the wall [4]. A round jet differs from the flat case because the shear layer in the round jet is able to transfer energy throughout its periphery so the wall effects on the shear layer are lessened; still, the wall has a substantially impact on the jet behavior [11]. This
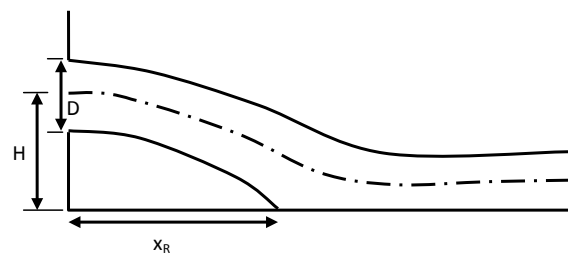

Figure 1. The height (H), jet diameter (D) and reattachment length (x_R) are important parameters describing offset jet flows.

alteration is likely to not only affect the behavior near the wall but also the mixing between the wall injector and other injectors in the engine as well. These effects impact engine performance. Finally, if the wall alters the dynamic behavior of the spray it may change the instantaneous mixing and, possibly, the combustion stability of the engine. For all of these reasons, it is important to understand the impact of a wall on the nearby spray.

The current work examines the effect of a single, offset wall on the spray produced by a gas-centered swirl-coaxial injector. This injector uses a (unswirled) high-velocity gas to strip liquid from an annular, swirling film. The wall is parallel to the injector axis, and two offset distances are compared with the free spray case. The attachment point of the spray, the spray's dynamic behavior and the change in spray boundary produced by the wall are all considered.

Experimental Set-up

The injector used in this study is illustrated in Fig. 2. Gas enters along a central, 6.35 mm radius post (r_p) with an L/D of ~14. The liquid enters through four, tangentially drilled holes each 1.535 mm in diameter. The gas velocity greatly exceeds the liquid velocity and the resulting shear at the interface strips the liquid film. The range of gas and liquid velocities are given in Table 1 along with the momentum flux ratio which is defined as $(\rho_l/\rho_g)(m_g/m_l)^2\{\tau(2r_o-\tau)/[r_o-(\tau+s)/2)]^2\}^2$ where ρ is the density, m is the mass flow rate, g denotes gas, l denotes liquid and the geometric parameters are given in Fig. 2 [12]. In all of the cases reported here the liquid film has been completely stripped prior to the injector exit, 35.2 mm downstream of the liquid inlet. The remaining geometric parameters of importance are the radius of the injector's outer cup, 7.62 mm, the liquid film's initial thickness, 1.65 mm, the height of the lip initially separating the gas and liquid, 1.52 mm, and the length of this separating lip, 3.2 mm. The main injector body is acrylic with the majority of the gas post being stainless steel.

The fluids used in this experiment are gaseous nitrogen and demineralized water. Their flow rates are metered with sonic nozzles and cavitating venturis, respectively. The nozzles, venturis and associated pressure transducers have been calibrated so that the error in mass flow rates is 0.227 g/s. The spray exits into atmospheric pressure air; however, since the experimental facility is well above sea level, the typical atmospheric pressure is 0.90 atm. More details on the set-up without the wall can be found in Schumaker et al. [12].

The wall was attached to the injector body so that its length was parallel to the injector axis. The wall was made of acrylic and waxed to improve its hydrophobic properties. Waxing reduced the pendant droplets on the
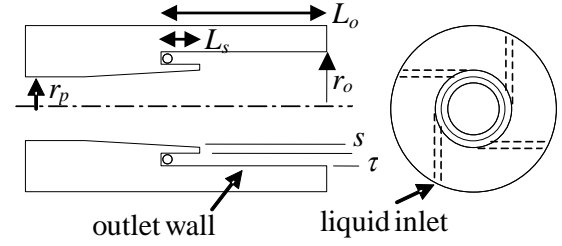

Figure 2. In this schematic of the GCSC injector, the gas flow is from left to right while the liquid enters the tangential holes. The injector outlet diameter, D, is equal to $2r_o$.

Wall Offset Ratio	Liquid Flow Rate (kg/s)	Gas Flow Rate (kg/s)	Mom Flux Ratio	Re_{dp}
∞	0.0441	0.0350	199	389881
∞	0.0448	0.0450	320	501275
∞	0.0369	0.0454	478	505731
∞	0.0484	0.0685	633	763053
∞	0.0441	0.0686	763	764167
1.16	0.0441	0.0352	202	392109
1.16	0.0448	0.0448	316	499048
1.16	0.0370	0.0458	486	510187
1.16	0.0482	0.0688	643	766394
1.16	0.0441	0.0682	755	759711
0.83	0.0441	0.0347	195	386539
0.83	0.0447	0.0448	319	499048
0.83	0.0369	0.0454	479	505731
0.83	0.0484	0.0688	638	766394
0.83	0.0440	0.0684	762	761939

Table 1. The operating conditions investigated in this study are given here.

wall's surface, which interfere with the imaging near the wall, but it did not eliminate them. The wall was 246 mm wide and 304.8 mm long. The joint between the wall and the injector body was sealed using vinyl tape to prevent air entrainment through the seam. There were no side walls or other spray enclosures in the vicinity of the spray. It has been shown that side walls improve the two-dimensionality of planar offset jet flows by preventing outside air entrainment [4], but this step was not taken due to the already complex three-dimensionality of the current flow, to enhance viewability and to allow future comparisons to fully enclosed offset sprays.

Two different offset distances are considered here and compared to the flow with no wall present. Wall offset distances were either 5 mm or 10 mm from the edge of the injector outlet. The offset ratio, that is the ratio of wall offset (from jet axis, as shown in Fig. 1) to injector outlet diameter, H/D, was either 1.16 or 0.83. These distances are quite small compared with those

typically found in the literature for planar offset jets, but in the vicinity of those seen in round jet studies. The Reynolds numbers of the gas flow prior to liquid contact (based on the gas post diameter--$4m_g/(\pi d_p \mu)$— given in Table 1) are higher than typically seen in the literature. Many studies report, however, that above a threshold value, typically something in a range which assures that the flow can be considered fully turbulent [1, 4], Reynolds number has little effect on flow parameters such as reattachment length.

The spray produced by the GCSC injector is very optically dense and difficult to penetrate with conventional laser diagnostics. As a result, measurements of droplet size and velocities were not attempted. Instead, high speed shadowgraphy is employed to give statistics on global spray behavior. The images are obtained using a Vision Research Phantom v7.3 camera with a framing rate of 6688 frames per second. Typical images with the various wall distances are given as Fig. 3. The backlighting was provided by a 500 W halogen light. This light uses AC power and, as a result, the background exhibited frequencies in the range of 120 Hz resulting from the variations in the lighting. Luckily, this lighting variation does not affect the results as the measured spray parameters do not exhibit dominant frequencies near this value. Great care was taken to ensure the camera was perpendicular to both the injector outlet plane and the wall.

All of the data were processed using in-house Matlab (R2008b) functions. First, an average background image (taken every morning and just prior to or just after a new round of testing) was subtracted from each frame of video. A simple segmentation process using Otsu's method [13] was employed. Once the image was segregated, the spray boundary location was recorded and the width and centerline were calculated. Straight lines originating from the exit of the injector were fit to the boundaries; the slope of these lines is used as the spray half angle. A similar procedure is used to fit a line to the centerline data (with the line originating at the spray's center near the exit); the slope of this line indicates if the spray is leaning with respect to the injector axis (within the plane of the camera only). Spray angles and slopes were determined over a distance of half the initial spray diameter ($0.5d_0$), over a length equal to the initial spray diameter ($1d_0$) and over distances of twice and three times the initial spray diameter ($2d_0$ and $3d_0$). The initial spray diameter is the diameter measured from the time-averaged boundaries. Due to droplets adhering to the injector exit, diameters within 5-15 pixels (~0.5 to 1.5 mm), depending on the test, were unreliable; diameters were therefore set to be the minimum spray diameter which generally occurs within 20 pixels (< 2 mm) of the exit. Because the initial spread of the spray, the scale factors and other parameters differ slightly throughout the series of tests, the spray diameter varies with both operating condition and wall location. The Malab program also performs FFT's of various data such as spray angle and boundary location as functions of time. Frequency content of the spray was extracted from these results. Because the frequency data is sensitive to noise in the raw images, proper orthogonal decomposition and reconstruction of 5 modes are used for determination of the frequency data. More details on the determination of angles, frequencies and the proper orthogonal decomposition and reconstruction can be found in a companion conference paper [14].

Due to the nature of the data processing and the inherent unsteadiness of the sprays, accuracies and errors are difficult to determine. An examination of various segregation methods suggests that the boundaries can be determined within 2 pixels, ~0.25
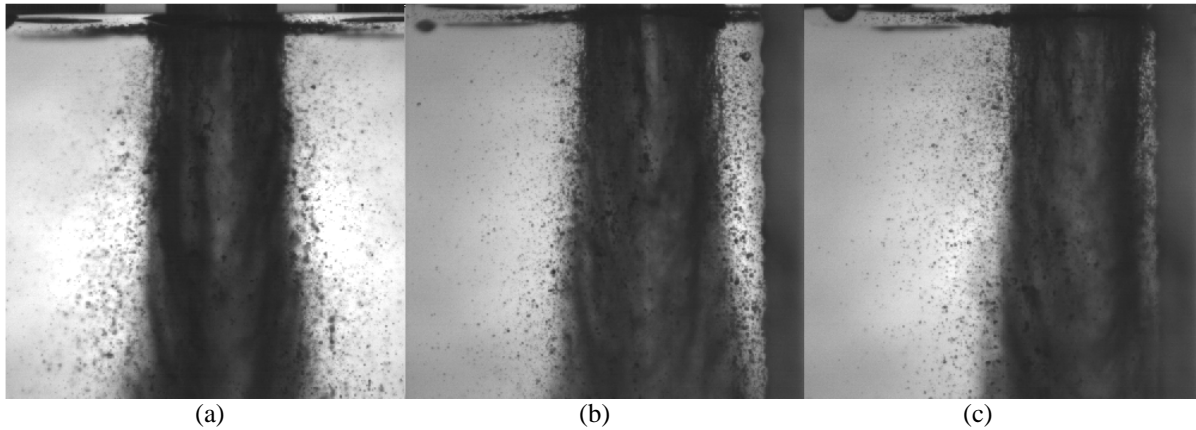

(a)   (b)   (c)

Figure 3. Typical images from the highest momentum flux ratio are shown here for the free spray (a), the 1.16 offset ratio wall (b) and the 0.83 offset ratio wall (c). The field of view in these images extends approximately 50 mm downstream.

mm, on average. Instantaneous, localized values can differ by 40 pixels (~4.5 mm) or more at some points, but are generally limited to under 10 pixels (~1.1 mm) [14]. Differences vary with lighting, spray density, droplet sizes and scale factors, however. Averaged boundaries are considered here to be accurate within +/- 0.25 mm and instantaneous boundaries are considered accurate to within +/- 1 mm; however, these accuracies should be considered notional and not exact values over the entirety of the conditions presented here. The standard deviation could be given as an indication of the accuracy, but these sprays are not steady and instead their value largely reflects the real variability within the data. It should also be noted that despite difficulties in assessing true accuracy, the results are reproducible regardless of personnel because the data processing is automated.

Results and Discussion

The results presented here are for the spray relatively close to the injector outlet, to a downstream distance of 50 mm. This distance is just over 3 times the injector diameter and about 3 times the measured initial spray diameter. While the majority of the graphs show only the highest momentum flux ratio case, the results apply to all momentum flux ratio conditions unless otherwise noted. Over the 50 mm distance the spray with a wall at an offset ratio of 1.16 is qualitatively similar to the free spray (i.e., spray with no wall present). The spray does not attach to the 1.16 offset ratio wall over the 50 mm distance and there is no obvious bias in the trajectories of large droplets or ligaments within the spray. In this case "large" indicates the liquid structures which can be distinctly identified as compared to the "small" droplets which appear only as the main shadow part of the shadowgraphy images. The 0.83 offset ratio wall, on the other hand, looks quite different. The spray curves noticeably towards the wall and attaches to it. The spray away from this wall does not look appreciably different from a qualitative standpoint. Typical images from the three separate wall distances are shown in Fig. 3. Even though the spray curves towards the wall in the 0.83 offset ratio case, the large ligaments and droplets in the spray do not appear to alter their path in relation to the main spray body—despite the strong gas flow the largest droplets do not follow the flow. The size of these structures plays a role in this behavior, but they also tend to be on the periphery of the spray so that they are either already headed towards the wall or are far from the wall and somewhat sheltered from it by the main gas jet.

Droplets cling to the wall and a film is formed on the wall at both offset ratios. Even though the main body of the spray does not attach to the farther-spaced wall over the 50 mm distance, there is sufficient mass in the large droplets on the periphery of spray to create a wetted wall. This film is never very thick and is not visible in the view with the camera parallel to the wall. However, when the camera is placed perpendicular to the wall, looking through the acrylic wall, the film is visible. An exact initial point for the film is difficult to obtain, but droplets and sporadic rivulets are visible within a few millimeters of the injector outlet. These droplets and rivulets have accumulated to a point that could easily be considered a film by 30 mm downstream (depending on operating condition) on the 1.16 offset-ratio wall. For the closer wall spacing, this film is strongly established by 15 mm, but, again, droplets and rivulets are seen nearer to the injector outlet. Even in this closer wall set-up the film is not visible (see Fig. 3c); the lack of visibility is likely the result of the small maximum thickness the film is able to obtain due to the strong shear produced by the high velocity gas flow.

As anticipated, the reattachment length (measured here only for the 0.83 stand-off ratio) shows little variation with Reynolds number or momentum flux ratio. The test-to-test variation is well within the standard deviation of the location. The reattachment point accuracy is less than the accuracy of the boundary location because it involves error in both the boundary and the wall location and, as a result, the variation is likely at the limit of the accuracy of the measurements. The average reattachment length, across operating conditions, is 28.2 mm with a standard deviation around 1.7 mm for most of the conditions tested. For the lowest momentum flux ratio, a case where the spray boundaries exhibit a noticeable and strong frequency [14], the standard deviation is much larger, 4.1mm. Exact values for each operating condition are given in Table 2. The reattachment point is not steady, even at the higher momentum flux ratios which have smaller variations, and can be observed to change positions very rapidly moving one or more millimeters from frame to frame—on the order of 0.15 ms. The ratio of reattachment length to initial jet diameter (x_R/D) is 1.85; literature values for single-phase jets at Reynolds number of 20,000 is on the order of 1 to 1.5 for two-dimensional offset jets near this offset ratio [3]. The current results agree surprisingly well with those for

Mom Flux ratio	x_R (mm)	Standard Deviation	x_R/D	x_R/H
195	27.1	4.1	1.78	2.15
319	28.7	1.9	1.88	2.27
479	28.7	1.6	1.88	2.27
638	28.5	1.5	1.87	2.26
762	28.0	1.6	1.83	2.22

Table 2. The reattachment length is relatively constant despite changes in Reynolds number and momentum flux ratio.
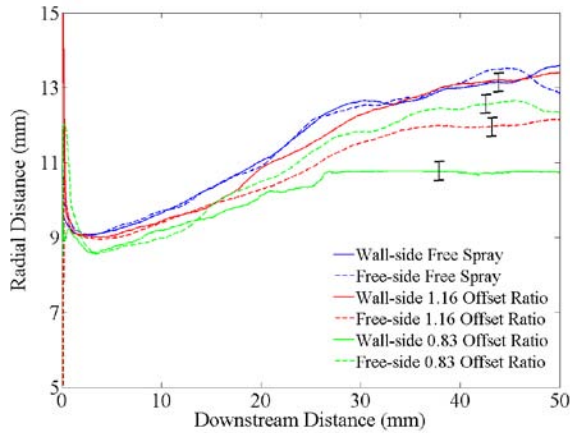
Figure 4. The distance from the centerline of the initial spray to the boundaries is plotted here for the highest momentum flux ratio. These are time averaged boundary locations over 3000 frames.

Figure 5. The time-averaged width of the spray decreases as the wall is moved closer to the spray's centerline. Here the width of the highest momentum flux case is averaged over 3000 frames.

two-dimensional, single-phase jets. Overall, however, the small variation in attachment both with condition and time suggests the wall-injector compatibility is favorable for the GCSC injector in terms of using the attached flow to cool the wall.

The qualitative observations of the spray are supported by the averaged and instantaneous boundaries, widths and centerlines determined from image processing. However, these quantitative values show that the wall has a measurable effect on the spray even at the 1.16 ratio. Figure 4 shows time-averaged distance from the centerline for all three wall locations and for both the free and wall side of the spray. Near the injector outlet there is little difference in the boundaries from the near-wall to free sides, although there is a slight decrease in initial spray diameter when a wall is present and as the wall is moved closer to the spray. At about 15 mm (L/D~1) downstream, the wall-side and free-side boundaries begin to depart if there is a wall present. For the range of conditions examined here departure always begins in the range of 14-18 mm. For the 0.83 stand-off ratio condition, the wall-side boundary is noticeably affected by the wall and becomes attached while the free-side boundary spreads at a faster rate than the wall-side boundary but at a slower rate than the free spray. This behavior is expected from the typical single-jet behavior where the entire jet curves towards the wall. The behavior of the spray placed 10 mm from the wall (i.e., 1.16 offset-ratio) is not what might be expected from this generalized single-jet behavior. When the two boundaries depart, the side nearest the wall has a profile essentially identical to the free spray. Meanwhile, the free-side boundary expands at a slower rate so that the spray edge is measurably closer to the centerline. The reason for this unintuitive behavior is not yet clear. The
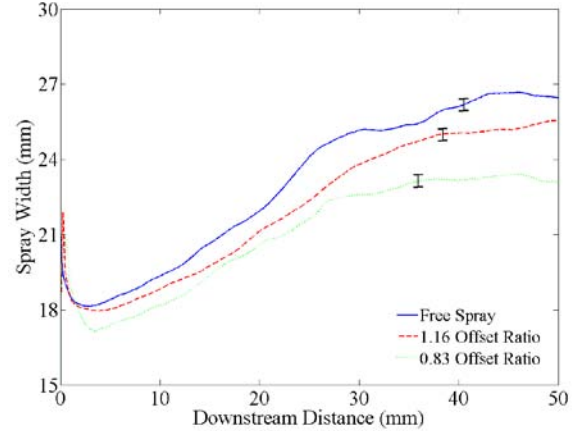
spray does eventually attach to the wall, farther downstream than the current examination, so the wall side boundary will diverge from the free spray at some point. The available literature on three-dimensional, single-phase jets does not clearly indicate if this behavior is a departure from the single-phase case. However, the wetted wall may play a role given the findings by Bernal and Madnia [5] that (for H/D=1.5) jets near free surfaces had the same growth rate perpendicular to the free surface as a free jet would while the growth rates near walls are decreased in this dimension [2]. An examination of the width shows that the overall growth rate of the spray is decreased here as would be expected from the hard surface of the wall (Fig. 5). The wetted wall also impacts vortex breakdown which plays an important role in offset single-phase jet behavior [5]. Finally, the ability of the wetted wall to allow some motion at its effective surface may alter the entrainment rates. In general, it appears that the jet is curving towards the wall so that the spread into the atmosphere is lessening but near the wall the surface is at enough distance that it is not yet limiting the spread of the jet in that dimension. It should further be noted that Fig. 4 contains time-averaged boundaries, so the difference in boundaries is larger than the estimated uncertainty. The difference between the free spray and the free-side boundary of the spray with the 1.16 offset-ratio wall is nearly identical to the standard deviation in the boundary location with the difference being slightly larger in most of the cases examined here.

The variability (i.e., standard deviation) in boundary location is nearly identical in all instances except the wall-side boundary with the 0.83 offset-ratio wall. In this nearest-wall boundary the variation is substantially reduced prior to the attachment to the wall and essentially zero thereafter. As with the other

values, the standard deviation increases in the downstream direction. In all but the nearest-wall boundary, the increase continues throughout the 50 mm distance examined. For the nearest-wall boundary, the variation reaches a maximum at a location which roughly corresponds to the location where the two boundaries, wall- and free-side, begin to depart from one another. These findings are illustrated in two different ways by Figures 6 and 7. The wall has the ability to damp some of the variability of the spray but only in an area very near the wall—here, only in the wall-side boundary when the wall is 5 mm from the injector outlet. Even the free-side boundary of the spray with the 0.83 offset-ratio wall did not exhibit any damping of motion, i.e. decrease in standard deviation. The variations in the centerline are already substantially smaller than those for the boundaries and the wall location shows no ability to further decrease them. As would be expected from the boundary deviations, though, the width variation does decrease slightly for the 0.83 offset ratio wall while the larger offset ratio shows variations which are essentially equal to those in the free spray. The condition with the most unsteadiness, the lowest momentum flux ratio condition, does not show a decrease in width variability when the wall is close, so the wall is unable to damp the strong global oscillations present in this condition (see Fig. 7). This inability to damp or change these oscillations also suggests that the unsteadiness arises inside the injector and not as a result of vortex breakdown in the sudden expansion at the injector outlet. The wall also has some impact on the nature of the variation. When the wall offset by a ratio of 0.83, more locations on the boundary deviate (from the average) towards the wall than away from the wall. Obviously, then, while more numerous, the departure towards the wall is reduced in magnitude. These

findings hold true for both the free- and wall-side boundaries with the 0.83 offset ratio wall. In an engine, then, the wall could create less unsteadiness in mixing with a neighboring element located farther from the wall. No statistically significant change is seen in the cases with the 1.16 offset ratio wall, however, so to impact mixing in this way, the wall must be closer than a ratio of 1.16.

Given the expansion of the boundaries, a difference in spray angles is expected as the wall location changes. Angles are, however, measured starting from the injector outlet and there is little variation in boundaries in that region, so this difference is likely to be small. Spray angles are also susceptible to noise, even over small distances and, as a result, they are more uncertain
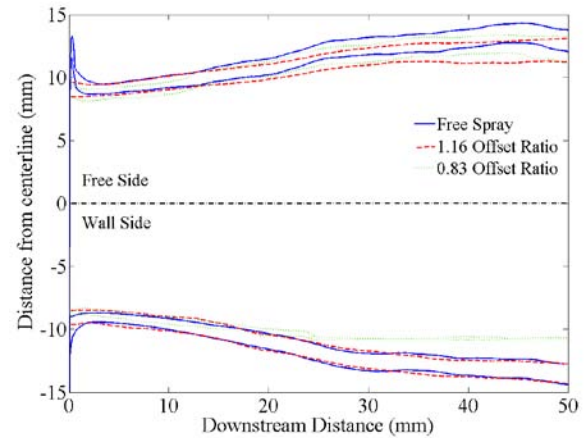

Figure 6. The bands over which the spray varies are illustrated for the highest momentum flux ratio. At each measured location (pixel) this graph gives the averaged boundary plus (and minus) the standard deviation at that point. The wall is located at the bottom of the graph.
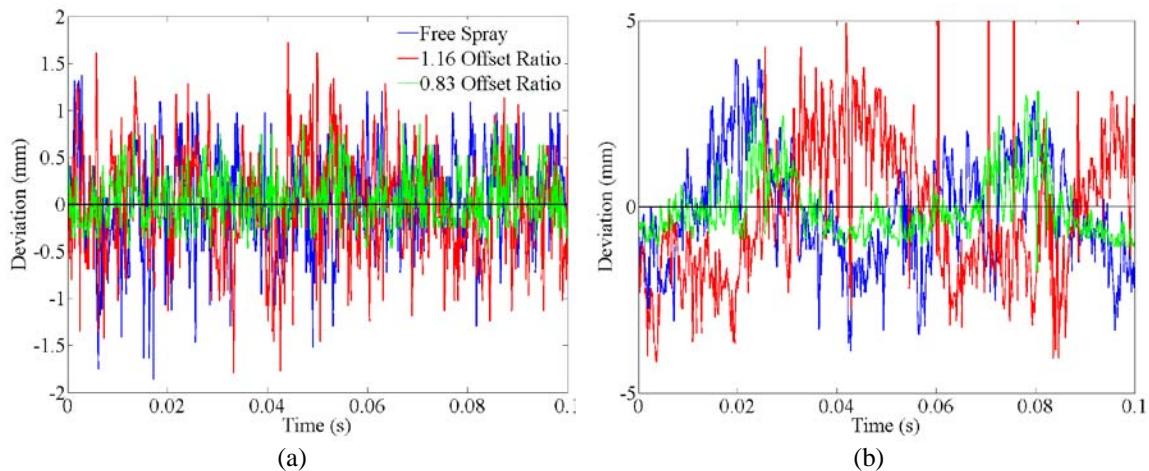

Figure 7. The deviation of the wall-side boundary from the average is shown over 0.1 seconds for (a) the highest momentum flux ratio and (b) the lowest momentum flux ratio tested.
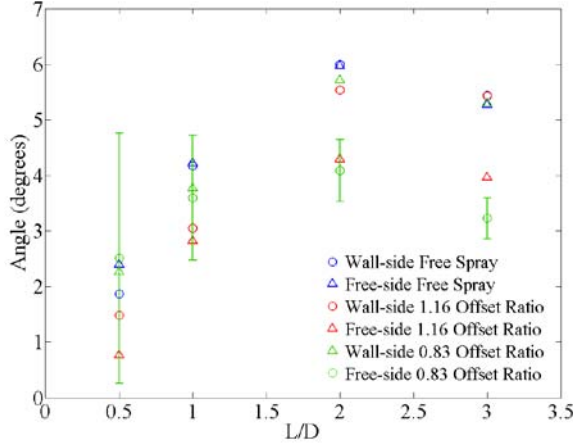
Figure 8. The angles fit to the averaged boundaries, averaged over 3000 frames, are plotted for the highest momentum flux ratio.

than the boundary measurements. This susceptibility to noise is particularly noticeable when the data is fit over $0.5d_0$ only, resulting in the inability to observe consistent changes in spray angle behavior with wall location or from wall-side to free-side boundary. Even when the noise is mitigated by fitting angles to averaged boundaries, where the uncertainty is only +/-2 pixels, the accuracy of the angles is insufficient to capture an difference in the angles. Over $1d_0$, $2d_0$ and $3d_0$ the susceptibility to noise is lessened as is the uncertainty produced by the uncertainty in averaged boundary location, and some trends are observed (see Fig. 8 for an example). Over the $1d_0$ distance the angles were nearly equal within the expected accuracy regardless of how close the boundary was to the wall or how close the wall was to the spray centerline. At $2d_0$ and $3d_0$ the sprays with 0.83 offset ratio walls have become attached to the wall, so a comparison of their spray angles is not necessarily meaningful; however, they are presented here for the sake of completeness. As expected from the boundary behavior, over the $2d_0$ and $3d_0$ distance a 0.83 offset ratio wall produces spray angles at the wall side that are smaller than on the free side while the opposite is true for the 1.16 offset ratio wall. Comparing the effect of the wall location over the $2d_0$ and $3d_0$ distances, the spray angles at the wall-side are the lowest for the nearest wall (remember, again, that the spray reattaches at roughly $1.5d_0$) while the wall-side angles are similar for the 1.16 offset ratio wall and no wall cases. The spray angles for the free-side of the spray are similar for the 0.83 offset ratio wall and no wall cases while they are lower for the 1.16 offset ratio (farther) wall. Again, these results hold true for the $2d_0$ and $3d_0$ distances. In summary, the angles are essentially equal at $2d_0$ and $3d_0$ except for the wall-side angle with the 0.86 offset ratio wall and the free-side angle with the 1.16 offset ratio wall. The wall-side angle for the 0.86 offset ratio wall is consistently lower

than the free-side of 1.16 offset wall; however, this difference is only statistically significant at the $3d_0$ distance. As can be seen from the width and boundary behavior as well as in Fig. 8, the spray angles generally increase as longer downstream distances are considered up to the $2d_0$ distance after which they level off. The variation (i.e., standard deviation) in angle is generally equal for both sides of the spray and only decreases for the wall-side boundary at the 0.83 stand-off ratio, similar to the standard deviation in the boundary locations. However, the variations in the wall-side spray angle with the 1.16 stand-off ratio wall tend to be very slightly larger for spray angles determined over the $1d_0$ and $2d_0$ distances.

The above results highlight that the wall may act as a stabilizing influence, but it appears to only be effective very near the wall. However, the standard deviation results apply to random, chaotic motions as well as to organized motions. Random motions tend to be more tolerated in many applications whereas organized motions may lead to undesirable effects including catastrophic events such as combustion instabilities. The effect of the wall on organized motions can be more strongly illustrated through examination of the frequencies. In general, the spectral energy of parameters near the wall with a 0.86 offset ratio is lower than those of other parameters. (For example, the overall and peak values show in Fig. 9 are substantially lower for the 0.86 offset ratio.) The free-side boundary is not affected by the wall as much—its spectral energy is near that of the farther spaced wall and the free spray. In the case of large-scale periodic movement, as seen in the lowest momentum flux ratio case, the wall does have some damping effect as seen in Fig. 9a, but even near the wall the strong frequency is still clearly visible. In addition to suppressing some of the organized motion, the wall can change the dominant frequencies in some cases. For example, the wall case has a dramatic effect on the dominant frequency at the highest momentum flux ratio increasing it from 6.5 Hz to 32.7 Hz (Fig. 9b). However, this shift is probably not a complete change in behavior as the higher frequency is, within the frequency resolution available, a multiple of the lower frequency. The reason for the increase in frequency is currently unclear, but the result does highlight that the wall effects on the spray are not limited to suppression near the wall and that the some of the unsteadiness observed GCSC injectors originates within the injector body and not as a result of the sudden expansion to the atmosphere. This result supports earlier findings for free sprays [10].

Conclusions

As would be expected, a wall can have a tremendous impact on a gas-dominated spray. As in the single-phase case of an offset jet, the offset spray
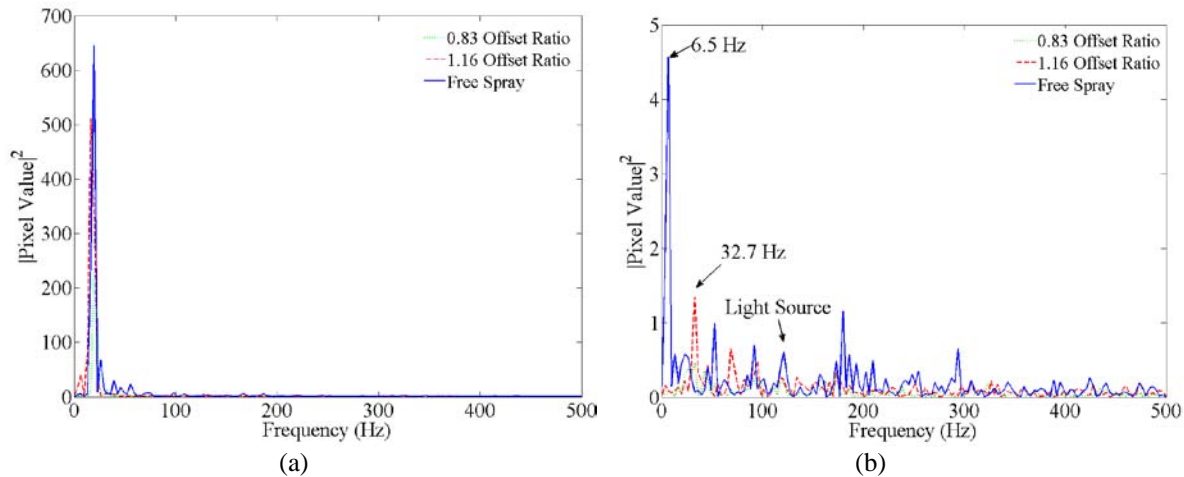
Figure 9. For conditions with strong organized motions, such as the lowest momentum flux ratio (a), the wall has little impact on the dynamic behavior. In other cases, such as the highest momentum flux ratio (b), the wall alters the dominate frequency.

moves towards and will eventually attach to the wall. The distance from the spray centerline to the wall has a marked impact on the spray behavior. As the wall is moved nearer to the spray, the reattachment length shortens. Because the field of view examined in this paper was limited to 50 mm downstream, reattachment was only studied for the nearest wall, with a stand-off ratio of 0.83. With this wall distance, the ratio of reattachment length to outlet diameter is 1.86; this result compares surprisingly well with results for two-dimensional, single-phase flow. The boundaries of the spray behave as would be expected for the free spray (both sides of the spray are essentially identical) and the nearer—0.83 offset ratio—wall (the wall side attaches to the wall and the free side expands less than a free spray would). With the 1.16 offset ratio wall the sprays did not behave as anticipated. The distance from the centerline to the free-side boundary was larger than the distance to the wall-side boundary once the two boundaries departed from one-another. The numerous potential impacts of the wetted-wall boundary conditions and the jets' three-dimensionality are likely candidates as the cause of the unexpected behavior. Despite this anomalous behavior the spray width behaves as expected with a decrease in spreading as the wall is moved closer to the spray's centerline. Over a distance equal to the sprays' initial diameters the wall has little impact on the spray angle; for spray angles determined over longer distances, the angles behave as would be expected from the boundary behaviors.

The variability in the spray measured through standard deviation and spectral energy shows that the wall can suppress both random and organized motion. However, this suppression only occurs in the wall-side boundary when the wall is sufficiently close. An offset ratio of 1.16 was insufficient to suppress instabilities

but a ratio of 0.83 was adequate. However, only the instabilities near the wall are suppressed—the boundary away from the wall did not have a decrease in variability. It was also observed that the wall can change the frequency response of the spray. While a large shift in frequency was observed, the dominant frequency remained a multiple of that measured in the free spray, so organized motions do not appear to be truly disrupted by the wall.

Overall, the steadiness observed in the reattachment point is a favorable finding for wall-injector compatibility. The decrease in spray width, while not unexpected, can negatively impact mixing between injectors and must be accounted for in the design of engines. The wall has a slight stabilizing effect but at the distances studied is unlikely to have a strong impact on overall device performance or stability. While the current work has illustrated some of the global effects a wall has on a gas-dominated, two-phase jet, few conclusions can be drawn about the detailed underlying physics at work. Much additional work remains including investigations over larger fields of view and examinations of the effects additional walls.

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